

# Enhancing the detection probability of single waveguided-photon by cavity technique

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The resonant-cavity-enhanced (RCE) technique is an important approach to increasing the detection efficiency (DE) of typical free-space coupling photons. Here, we show that such a technique can also be utilized to increase the detection probability (DP) of a single waveguide-coupled photon. Based on a fully quantum mechanical theory in real space, we exactly calculated the absorption probability of a single photon for a two-level detector next to the waveguide. We find that the DP of the waveguide photon for the detector in a waveguide-coupled ring cavity is significantly higher than that for the bare detector directly coupled to the photon. Physically, the DP of the photon for the bare detector next to the waveguide is always limited by the finite transmission and reflection probabilities of the photon. The cavity technique is used to store the photon and thus increase its DP. The feasibility of the proposal with current integrated optical devices is then discussed.

PACS number(s): 32.80.Qk, 42.50.Ct, 42.79.Gn

## I. INTRODUCTION

Single-photon detection is a well-studied but nonetheless hot topic in optical physics because it is related to various important applications, specifically the realizations of the optical quantum computation[1, 2], quantum information[3] and precise measurements [4]. Photon detections have been achieved by utilizing photomultiplier tubes (PMT), wherein the absorptions of the incident photons were converted into detectable electronic signals. In semiconducting detectors, specifically single-photon avalanche photon diodes (SAPD) [5], the signals related to photon-induced electron-hole pairs are probed. To decrease unwanted dark counts, low temperature detectors with quantum dots [6] and superconductors [7, 8] have also been developed.

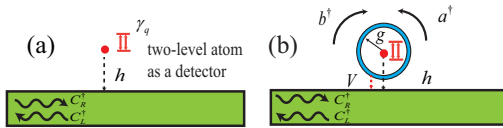


FIG. 1: Configurations of the detectors for single photons in the waveguide; (a) a bare two-level atom as a single-photon detector and (b) a two-level atom in a microring cavity as a single-photon detector. Here, the single-mode waveguide is denoted by the green channel, and the microring cavity is denoted by a blue circle. The two-level atomic detector is denoted by a red dot.

Recently, to decrease the loss of photons and achieve convenient optical device integrations on a chip, integrated photonic circuits [9, 10] have been paid substantial attention. In the waveguide, the photons are effectively confined in certain micro-structures and thus the relevant propagation losses can be minimized. Therefore, by integrating the waveguide and photonic devices simultaneously on a chip [11], the efficiencies of the photonic emission, traveling, routing, detection, etc. can be significantly increased. Although the trans-

port properties of single photons traveling along waveguide structures have been extensively investigated; see, e.g., [12–14], the research on the detection of the waveguide photons with integrated photon detectors is relatively sparse [17–24]. Typically, superconducting nanowire single photon detectors (SNSPDs) [17–22] and transition edge sensors (TESs) [23, 24] have been demonstrated for the waveguide-coupled photon detections. Note that the 20% DE (at telecommunication wavelengths) [17, 18, 20] of a single photon for *GaAs* SNSPD integrated waveguide-coupled detectors [25] has been experimentally demonstrated, which is substantially higher than those for the free-space coupling counterparts (usually  $\sim 10\%$  [26]). A higher DE could be achieved by further optimizing integrated waveguide-coupled detectors via further decreasing the coupling losses.

Given that the resonant cavity enhanced (RCE) technique has been extensively utilized to increase the DE of the usual free-space coupling photon detectors [27], it is expected that such a technique will also be useful for waveguide-coupled photon detectors. The applied RCE devices can store the detected photons in the cavity, and thus, the relevant DE can be increased. Various resonant cavity geometries, including the Fabry-Perot resonant cavity [27] and microring resonant cavity [28], have been successfully applied to increase the DEs of free-space-coupled photon detectors, i.e., *the photons propagate in free space until being absorbed by the detectors*.

In this paper, we first calculate the DP of the single photon confined in the waveguide by a bare two-level atom. It is shown that such a probability is quite low as a relatively low probability of the photon-induced atomic excitation. To enhance the probability of atom excitation, we propose an approach by using the RCE technique, i.e., a resonant microring cavity structure [14, 29, 30] (see also Fig. 1(b)), to transport the traveling photon along the waveguide into the cavity. Our discussion is based on a full quantum theory [12–14] for single photons transporting in real space and interacting with a two level detector in the resonant cavity. The detection of the single photon is implemented by probing the excitation probability of the two-level atomic detector coupled to the waveguide. Because the traveling waveguide photon is converted into a standing wave that is stored in the cavity, the DP of the

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single photon can be increased. The feasibility of the proposal is also discussed.

## II. DP OF A SINGLE PHOTON IN A WAVEGUIDE BY A BARE TWO-LEVEL ATOMIC DETECTOR

Following Ref. [13, 14, 16], the effective Hamiltonian describing a single photon propagating along a one-dimensional waveguide scattered by a single two-level atom can be expressed as

$$\begin{aligned} H_1/\hbar = & -iv_g \int dx \{C_R^\dagger(x) \frac{\partial}{\partial x} C_R(x) - C_L^\dagger(x) \frac{\partial}{\partial x} C_L(x)\} \\ & + \{ \int dx \delta(x) [hC_L(x)\sigma^\dagger + hC_R(x)\sigma^\dagger] + h.c\} \\ & + (\Omega_e - i\gamma_q)\omega_e^\dagger\omega_e + \Omega_g\omega_g^\dagger\omega_g. \end{aligned}$$

Here,  $C_{R/L}^\dagger(x)$  represents the bosonic creation operator at the position  $x$  of the photon traveling in the right/left direction.  $\Omega_e - \Omega_g \equiv \Omega$  is the atomic transition frequency,  $\omega_{g/e}$  represents the ground/excited state frequency of the atom, and  $\sigma^\dagger(\sigma) = \omega_e^\dagger\omega_g(\omega_e\omega_g^\dagger)$  is the creation (annihilation) ladder operator of the atom,  $v_g$  is the group velocity of the incident photon in the waveguide,  $\gamma_q$  is the dissipation rate of the excited atom, and  $h$  (with units of  $\sqrt{m}$  MHz to ensure consistent dimensions, more details can be seen in the Ref ([16]) is the efficient coupling strength between the atom and the waveguide photon. Obviously, the first and second parts in the above Hamiltonian describe the photon freely transporting along the waveguide and the bare atom, respectively. The third part describes the interaction between the atom and the photon in the waveguide.

The generic quantum state of the system can be expressed as

$$\begin{aligned} |\Phi_1(\tau)\rangle = & \int dx \{ \phi_R(x, \tau) C_R^\dagger(x) + \phi_L(x, \tau) C_L^\dagger(x) \} |0, -\rangle \\ & + e_q(\tau) \sigma^\dagger |0, -\rangle, \end{aligned} \quad (1)$$

which satisfies the Schrödinger equation

$$H_1|\Phi_1(\tau)\rangle = i\hbar \frac{\partial}{\partial \tau} |\Phi_1(\tau)\rangle. \quad (2)$$

Above,  $|0, -\rangle$  depicts the state of the system without any propagating photon in the waveguide, and the atom is in its ground state.  $\phi_{R/L}(x, \tau)$  is the single-photon wavefunction transporting in the  $R/L$  mode, and  $e_q(\tau)$  the excitation amplitude of the atom. The system wave function can be rewritten as  $|\Phi(\tau)\rangle = e^{-i\epsilon\tau}|\epsilon\rangle$ , with  $\epsilon$  being the eigenfrequency, and

$$\begin{aligned} |\epsilon\rangle = & \int dx [\phi_R(x) C_R^\dagger(x) + \phi_L(x) C_L^\dagger(x)] |0, -\rangle \\ & + e_q \sigma^\dagger |0, -\rangle. \end{aligned} \quad (3)$$

The coefficients in Eq. (4) are determined by

$$\begin{aligned} -iv_g \frac{\partial}{\partial x} \phi_R(x) + \delta(x) h e_q + \Omega_g \phi_R(x) &= \epsilon \phi_R(x), \\ +iv_g \frac{\partial}{\partial x} \phi_L(x) + \delta(x) h e_q + \Omega_g \phi_L(x) &= \epsilon \phi_L(x), \\ (\Omega_e - i\gamma_q) e_q + h^* \phi_R(0) + h \phi_L(0) &= \epsilon e_q, \end{aligned} \quad (4)$$

with  $\epsilon = \omega + \Omega_g$  and  $\omega = kv_g$ . Introducing the Heaviside step function  $\theta(x)$ , we have  $\phi_R(x) = e^{ikx}[\theta(-x) + t\theta(x)]$  and  $\phi_L(x) = r e^{-ikx}\theta(-x)$ , with  $t$  and  $r$  being the transmission and reflection amplitudes of the photon, respectively. Consequently, Eq. (5) can be further simplified as

$$\begin{aligned} -iv_g(t-1) + h e_q &= 0, \\ +iv_g(-r) + h e_q &= 0, \\ (\Omega - i\gamma_q) e_q + h^* \frac{1+t}{2} + h^* \frac{r}{2} &= \omega e_q \end{aligned} \quad (5)$$

To simplify the calculation, we have set the coupling strength between the waveguide and atom is real, i.e.  $h = h^* = |h|$ . The solution of the above equation reads

$$\begin{aligned} t &= \frac{(i\gamma_q + \omega - \Omega)}{(i\gamma_q + \omega - \Omega) + i\Gamma_1}, \\ r &= \frac{-i\Gamma_1}{(i\gamma_q + \omega - \Omega) + i\Gamma_1}, \\ e_q &= \frac{h}{(i\gamma_q + \omega - \Omega) + i\Gamma_1}, \end{aligned}$$

with  $\Gamma_1 = h^2/v_g$ . Generically, the normalized DP  $\eta_b$  of the photon reads

$$\eta_b = \frac{|e_q|^2}{|t|^2 + |r|^2 + |e_q|^2}. \quad (6)$$

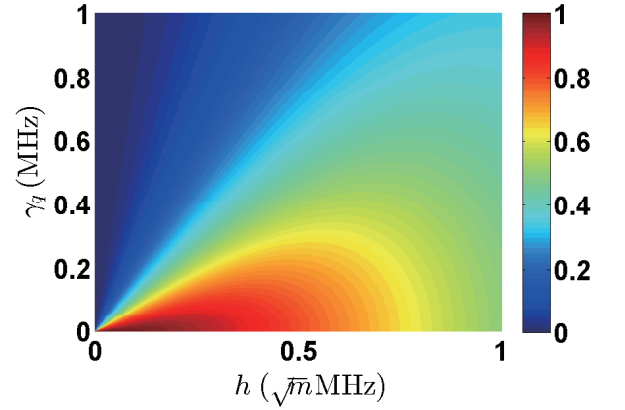


FIG. 2: DP  $\eta_b$  of a single confined photon by a bare two-level detector versus the atomic dissipation rate  $\gamma_q$  and the resonant (i.e.,  $\omega - \Omega = 0$ ) coupling strength  $h$  between the detector and photon. Here,  $v_g = 1$ .

Fig. 2 shows how the excitation probability  $\eta_b$  (i.e., the DP of the confined photon by a bare two-level detector) varies with the dissipation  $\gamma_q$  of the excited atomic state and the photon-detector resonant coupling strength  $h$ . For a defined atomic dissipation rate  $\gamma_q$ , the value of  $\eta_b$  is found to exhibit a maximal value when varying the photon-detector interacting strength. In addition, the peak value of  $\eta_b$  increases monotonously with decreasing atomic dissipation. The desired photon detection is usually achieved by probing the leakage of the population from the excited atomic state. This

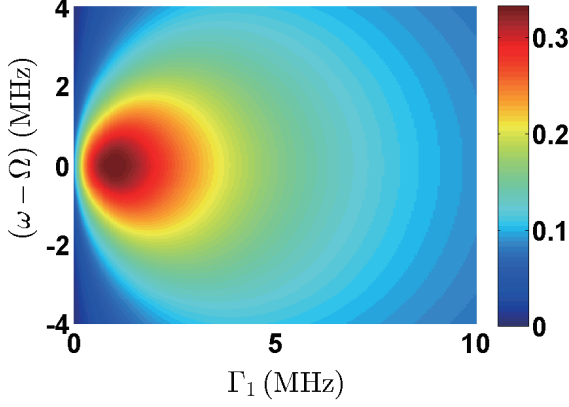


FIG. 3: DP of the single confined photon in the waveguide by the atomic detector with a defined dissipation  $\gamma_q/2\pi = 0.16 \text{ MHz}$ . The maximum of the DP is  $\eta_b = 33.22\%$  for the resonant photon.

implies that the dissipation of the detector atom should be sufficiently large; otherwise, its leakage cannot be measured. Moreover, when  $\gamma_q \sim 0$ , the resonant photon is fully reflected by the atomic detector, i.e.,  $|r|^2 \sim 1$  and  $|t|^2 \sim 0$ , even though the atom can still be temporally excited. In this case, the photon cannot be detected by the detector.

For a typical dissipation of the atomic detector, e.g.,  $\gamma_q/2\pi = 0.16 \text{ MHz}$  [30], Fig. 3 shows the DP of the single confined photon in the waveguide versus the effective atom-photon detuning  $\Delta \equiv \omega - \Omega$  and the effective atom-photon coupling strength  $\Gamma_1 = |h|^2/v_g$ . It is seen that, for the fixed dissipation  $\gamma_q/2\pi = 0.16 \text{ MHz}$  of the atomic detector, the DP of the photon exhibits a maximal value for certain parameters and varies symmetrically with the frequency of the incident light. For a defined  $\Gamma_1$ , the DP of the resonant photon is always higher than that of the off-resonant photon. Furthermore, for a defined atom-photon detuning, the DP of the photon exhibits a peak value, corresponding to an optimal effective atom-photon coupling. The maximum DP of the resonant photon by the present bare detector is approximately  $\eta_b = 33.22\%$ . This is low for desired quantum information processing on chip and should be increased.

### III. CAVITY-ENHANCED DP OF A SINGLE RESONANT PHOTON IN A WAVEGUIDE

It is well known that the microcavity technique has matured in recent decades. The RCE devices benefit from the wavelength selectivity and increased optics-matter interactions. As a consequence, RCE photodetectors can be thinner and smaller, thereby increasing the sensitivity of the photon response and thus the quantum efficiency of the photon detection. With such a technique, light with off-resonant wavelengths is rejected. In this section, we show that such a technique can also be utilized to increase the excitation probability of a single two-level atomic detector for waveguide photons.

The basic idea of the RCE technique is to convert a pho-

ton traveling along the waveguide into a standing wave in a cavity. We assume that the bare atomic detector is placed in a microring cavity with two degenerated whispering-gallery modes (WGMs), namely,  $a^\dagger$  and  $b^\dagger$  modes. Now, the effective Hamiltonian of the system reads

$$\begin{aligned} H_2/\hbar = & -iv_g \int dx \{C_R^\dagger(x) \frac{\partial}{\partial x} C_R(x) - C_L^\dagger(x) \frac{\partial}{\partial x} C_L(x)\} \\ & + (\Omega_e - i\gamma_q) \omega_e^\dagger \omega + \Omega_g \omega_g^\dagger \omega_g \\ & + (\omega_c - i\gamma_c) a^\dagger a + (\omega_c - i\gamma_c) b^\dagger b \\ & + \{ \int dx \delta(x) h [C_L(x) \sigma^\dagger + C_R(x) \sigma^\dagger] \\ & + \int dx \delta(x) [V_a C_R(x) a^\dagger + V_b C_L(x) b^\dagger] \\ & + [g_a a + g_b b] \sigma^\dagger + h.c. \}. \end{aligned} \quad (7)$$

Here,  $a^\dagger$  and  $b^\dagger$  are the Bosonic operators describing the anti-clockwise and clockwise WGMs in the microring cavity with the same frequency  $\omega_c$  and dissipation rate  $\gamma_c$ , respectively. The sixth and seventh terms in the Hamiltonian (9) are the interactions between the waveguide-cavity modes, and  $V_{a/b}$  and  $g_{a/b}$  describe the coupling strength between the  $a/b$  mode and the photon in the waveguide and the atom detector, respectively. Note that the efficient coupling strength  $V$  has the same dimensions as  $\hbar$ , and the unit of  $g$  is that of the frequency. The generic wave function of the present system takes the form

$$\begin{aligned} |\Phi_2(\tau)\rangle = & \int dx \{ \phi_R(x, \tau) C_R^\dagger(x) + \phi_L(x, \tau) C_L^\dagger(x) \} |0, 0, -\rangle \\ & + e_a(\tau) a^\dagger |0, 0, -\rangle + e_b(\tau) b^\dagger |0, 0, -\rangle \\ & + e_q(\tau) \sigma^\dagger |0, 0, -\rangle, \end{aligned} \quad (8)$$

where  $|0, 0, -\rangle$  represents the ground state of the system (i.e., there is no propagating photon in the waveguide, and the cavity and the atom are not excited). With the same approach used in Sec. II, for a single photon input along the waveguide from the left direction, the excitation probabilities of the atomic detector and the WG modes as well as the reflection and transmission amplitude of the incident photon are determined as follows:

$$\begin{aligned} -iv_g(t-1) + V_a e_a + h e_q &= 0, \\ +iv_g(-r) + V_b e_b + h e_q &= 0, \\ (\omega_c - i\gamma_c) e_a + V_a^* \frac{1+t}{2} + g_a e_q &= \omega e_a, \\ (\omega_c - i\gamma_c) e_b + V_b^* \frac{r}{2} + g_b e_q &= \omega e_b, \\ (\Omega - i\gamma_q) e_q + h^* \frac{1+t}{2} + h^* \frac{r}{2} + g_a^* e_a + g_b^* e_b &= \omega e_q. \end{aligned} \quad (9)$$

Solving the above equation, we have

$$\begin{aligned} e_q &= \frac{-2i\Lambda}{2i(2g^2 - AB) + 2\Theta + 4hgV}, \\ e_b &= \frac{-(2ig + hV)\Lambda}{(A + i\Gamma_2)[2i(2g^2 - AB) + 2\Theta + 4hgV]}, \\ e_a &= \frac{V[2i\Upsilon + 2\Theta + 4hgV] - (2ig + hV)\Lambda}{(A + i\Gamma_2)[2i\Upsilon + 2\Theta + 4hgV]}, \\ r &= \frac{-2\Lambda^2}{(A + i\Gamma_2)[2i\Upsilon + 2\Theta + 4hgV]}, \\ t &= \frac{(A - i\Gamma_2)[2i(2g^2 - AB) + 2\Theta + 4hgV] - 2\Lambda^2}{(A + i\Gamma_2)[2i\Upsilon + 2\Theta + 4hgV]}, \end{aligned} \quad (10)$$

with  $\Lambda = Ah + gV$ ,  $A = (\omega - \omega_c + i\gamma_c)$ ,  $\Upsilon = (2g^2 - AB)$ ,  $\Theta = A\Gamma_1 + B\Gamma_2$ ,  $B = (\omega - \Omega + i\gamma_q)$ , and  $\Gamma_1 = h^2/v_g$ ,  $\Gamma_2 = V^2/2v_g$ . We have assumed  $V_a = V_b = V = V^*$ ,  $g_a = g_b = g = g^*$  and  $v_g = 1$  for simplicity. Consequently, the normalized DP of the photon in the waveguide by the atom detector in the cavity reads

$$\eta_c = \frac{|e_q|^2}{|t|^2 + |r|^2 + |e_q|^2 + |e_a|^2 + |e_b|^2}. \quad (11)$$

For the optimized atom-cavity coupling strength  $g/2\pi = 0.29\text{MHz}$ , Fig. 4 shows how the DP of the resonant photon depends on the coupling strength  $V$  (between the photon in the waveguide and the cavity) and  $h$  (between the atom and the photon in the waveguide) for typical dissipation rates for the atom and cavity [30]:  $\gamma_q/2\pi = 0.16\text{ MHz}$  and  $\gamma_c/2\pi = 0.76\text{ MHz}$ . Specifically, one can observe the following:

- i) For a fixed coupling strength  $h$ , the DP obtains a peak value for certain selected values of  $V$ . However, for  $V/2\pi \geq 0.6\sqrt{m}\text{ MHz}$ , the DP monotonously decreases.
- ii) When  $V \sim 0$ , the photon can still be directly detected by the atom detector, although the probability is relatively low, e.g., the maximal value is  $\eta_c \sim 0.2$ .
- iii) Interestingly, there exists a cavity-enhanced ( $h, V$ )-regime (i.e., the yellow regime with  $\eta_c \geq 0.34$ ), wherein the DP of the photon in the waveguide is significantly increased compared to that for the bare atom detector.

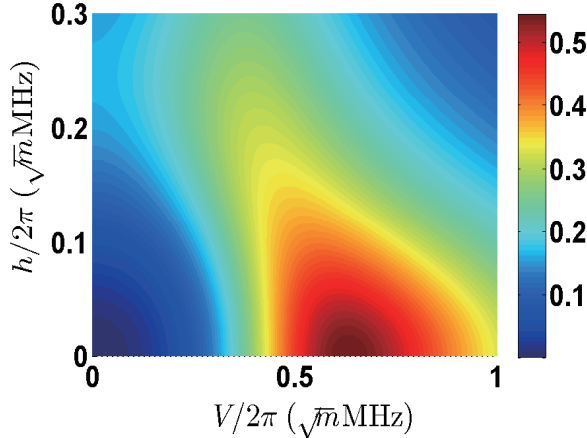


FIG. 4: DP  $\eta_c$  of the photon for a two-level atomic detector in a microring cavity versus the coupling strength  $V$  (between the photon in the waveguide and the cavity) and  $h$  (between the atom and the photon in the waveguide). The other parameters are  $\gamma_q/2\pi = 0.16\text{ MHz}$ ,  $\gamma_c/2\pi = 0.76\text{ MHz}$  [30], and  $g/2\pi = 0.29\text{ MHz}$  when we properly varied to achieve the maximum DP.

We now analyze the maximum value of  $\eta_c$ , which is found (in Fig. 4) to be  $\eta_c = 54.39\%$  for  $h/2\pi = 0$  and  $V/2\pi = 0.61\sqrt{m}\text{ MHz}$ . This corresponds to the very weak atom-waveguide coupling, i.e.,  $h \sim 0$ , and the phase- and magnitude-matching conditions

$$\Gamma_2 V g h = 0, \quad (12)$$

and

$$(\gamma_c - \Gamma_2)[2g^2 + \gamma_q(\gamma_c + \Gamma_2) + \gamma_c\Gamma_1] + g^2V^2 - h^2\gamma_c^2 = 0, \quad (13)$$

respectively, are satisfied. As a consequence, the optimized coupling strength  $g$  (between the atom and the cavity) should be designed as  $g = \sqrt{(\Gamma_2^2 - \gamma_c^2)\gamma_q}/\sqrt{2\gamma_c} \approx 1.82\text{ MHz}$ , and thus,  $g/2\pi \approx 0.29\text{ MHz}$ . Physically, the matching conditions demonstrated above imply that the photon in the waveguide is maximally (with 82% probability) converted in the cavity. Thus, the DP of the photon for the atom detector in the cavity is maximal.

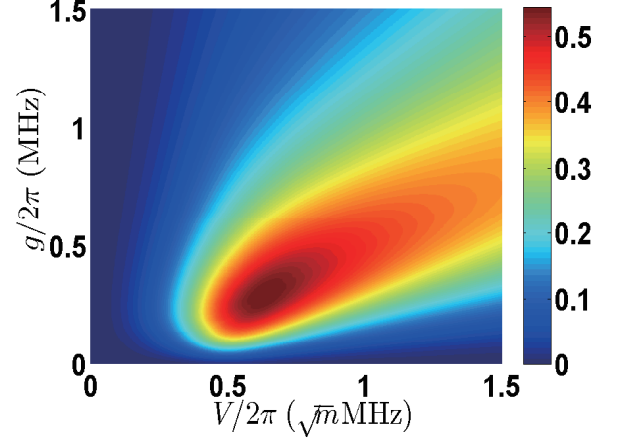


FIG. 5: DP  $\eta_c$  of the photon for a two-level atom detector in a microring cavity versus the coupling strength  $V$  (between the photon in the waveguide and the cavity) and  $g$  (between the atom and cavity). The parameters are  $\gamma_q/2\pi = 0.16\text{ MHz}$ ,  $\gamma_c/2\pi = 0.76\text{ MHz}$ , and  $h = 0$ .

This can be verified further using the numerical results shown in Fig. 5, which shows how the parameters  $g$  and  $V$  influence the DP of the photon. Here, the interaction between the atom and the photon in the waveguide is negligible due to the screen of the cavity. Note that at the maximal DP point, the reflection probability  $|r|^2$  of the photon in the waveguide remains non-zero (although  $|t|^2 \sim 0$ ) due to the existence of the atom detector in the cavity.

Fig. 6 shows that at the maximal DP point (with the optimized atom-cavity coupling strength  $g = 1.82\text{ MHz}$ ), the reflection probability of the photon is  $|r|^2 \approx 18.00\%$ ; the excitation probability of the  $a$ - and  $b$  modes in the cavity are  $|e_a|^2 \approx 26.81\%$  and  $|e_b|^2 \approx 1.65\%$ , respectively.

#### IV. CONCLUSIONS

In summary, we propose an approach based on a full quantum mechanic theory in real space to increase the DP of a single photon transporting along a one-dimensional waveguide. For a bare detector, we found that the DP is related to the dissipation rate of the atom and the atom-photon coupling strength. Typically, for a definite atomic dissipation, e.g.,



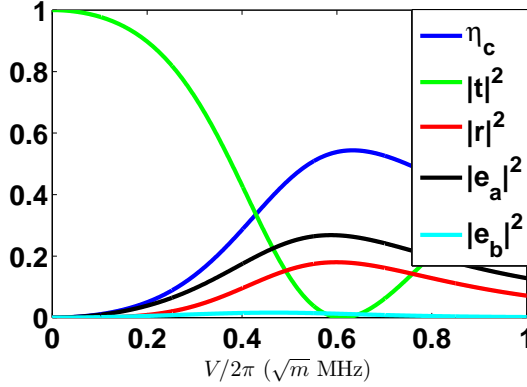


FIG. 6: DP and transport parameters of the photon in the waveguide, e.g., the detection, reflection and transmission probabilities etc. versus the coupling strength  $V$ . Here, the dissipation rates of the cavity and atom are set to  $\gamma_q/2\pi = 0.16$  MHz and  $\gamma_c/2\pi = 0.76$  MHz, and the coupling strength of the atom and the photon in the waveguide is  $\hbar = 0$ .

$\gamma_q = 0.16$  MHz, the maximum DP of the resonant photon in the waveguide for the bare detector is 33.22%. However, if the atom detector is placed adjacent to a microring cavity, then the traveling photon can be transported into the cavity and stored as standing wave modes. This increases the DP of the photon. Indeed, our analytical and numerical results show that the DP of the photon in a waveguide for the detector in a cavity can be significantly increased, and the maximal value of this probability can reach 54.39%. This again suggests that the RCE technique, used successfully to increase the detection efficiency of the photons in free space, can also be utilized to enhance the DP of a single photon in waveguide structures. In principle, by integrating a series of cavity as the reflectors [22] the ideal detection (i.e., its DP approaches to

100%) of the waveguide photons is feasible.

Hopefully, our proposal is feasible and can be directly applied to current integrated optoelectronics for optical quantum information processing on chips. Integrating the waveguide device and the photon detector on a chip is realizable with current integrated photonic techniques [17, 18]; the quantum efficiency of a waveguide nanowire superconducting single-photon detector has been increased to 20% [20]. In addition, in Ref. [31], a system consisting of quantum dots (artificial atoms could be used as photon detectors) in a cylindrical glass waveguide were fabricated. Furthermore, WGMs have been observed in a GaN-based microdisks [32]. Therefore, with current integrated optical techniques, the increased DP of the photon in a waveguide proposed in this paper should be feasible.

It is worth emphasizing that the physical mechanism presented here to detect the waveguide photon is different from those in the SSPDs [18]. Cooper pairs in superconductors are the collective elementary excitations of electrons and are not local. Photon detection by the SSPDs is implemented by probing the disappearance of these elementary excitations by amplifying the absorption effects of the photon. In the present model, a single photon is detected by probing the induced excitation of a single two-level atom. Therefore, in principle, the previously demonstrated SSPDs should not be modeled simply as a single two-level detector. However, whether a series of two-level detectors can be integrated to describe the SSPDs remains an open question and requires further investigation.

## V. ACKNOWLEDGMENTS

This work was supported in part by the National Fundamental Research Program of China through Grant No. 2010CB92304 and the National Science Foundation grant Nos. 11174373, 61301031, U1330201.

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